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# Application of Canadian Standards Association guidelines for geologic storage of CO<sub>2</sub> toward the development of a monitoring, verification, and accounting plan for a potential CCS project at Fort Nelson, British Columbia, Canada

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## Abstract

The feasibility of a carbon capture and storage (CCS) project at the Fort Nelson Gas Plant in British Columbia, Canada, has been conducted. The feasibility study included the collection of baseline characterization data, static and dynamic modelling efforts, two rounds of risk assessment, and the development of a draft monitoring, verification, and accounting (MVA) plan. Those activities have been compared to the Canadian Standards Association (CSA) standard for geologic storage of carbon dioxide. Although the remote location, difficult terrain, and extreme climate of the potential injection site make MVA challenging, cost-effective MVA that meets or surpasses the CSA standards is achievable.

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**Keywords:** Saline formations; feasibility study; geologic storage; CSA standards for geologic storage; monitoring

## 1. Introduction

In 2003, the U.S. Department of Energy (DOE) established seven Regional Carbon Sequestration Partnerships (RCSPs) to help develop the technology, infrastructure, and regulations to implement large-scale carbon dioxide (CO<sub>2</sub>) storage in different regions and geologic formations in the United States. Phase III of the program includes

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the implementation of large-scale (1 million tonnes or more total) projects that will demonstrate the long-term, effective, and safe storage and utilization of CO<sub>2</sub> in geologic formations throughout the United States and portions of Canada. The goals of the demonstration projects are to 1) provide scientific data to validate the capacity estimates to within  $\pm 30\%$  for deep saline formations, where few data currently exist; 2) assess the effects of reservoir heterogeneity on the performance of the storage operations to contact the pore space and maintain injectivity; 3) validate the reservoir models against field data, implement mitigation strategies to reduce potential hazards, and verify the fate of the injected CO<sub>2</sub> using the most advanced monitoring networks applied to date; and 4) demonstrate that the projects are representative of the regional geology to store large volumes of CO<sub>2</sub> emissions generated from major point sources. The Plains CO<sub>2</sub> Reduction (PCOR) Partnership, led by the University of North Dakota Energy & Environmental Research Center (EERC), together with its partner Spectra Energy Transmission (SET) conducted the Fort Nelson Carbon Capture and Storage (CCS) Feasibility Project (Fort Nelson project) in order to help achieve the program goals.

## 2. Overview of the Fort Nelson project

The Fort Nelson project is located in northeastern British Columbia within the northwestern portion of the Alberta Basin (Fig. 1). From 2009 to 2012, the EERC and SET conducted activities to investigate the feasibility of a CCS project to mitigate CO<sub>2</sub> emissions produced by SET's Fort Nelson Gas Plant (FNGP) as a waste stream from natural gas processing. The concept for the CCS project would be to compress the CO<sub>2</sub> stream to a supercritical state and transport it via pipeline approximately 15 km to an injection site. The injection target, or sink, being considered consists of brine-saturated carbonate rocks (limestone and dolomite) of a formation in the Devonian-age Elk Point Group. The proposed injection zone is capped by more than 550 meters of Fort Simpson and Muskwa shale. These shale formations are expected to function as an impermeable seal. A technical team that includes SET, the EERC, and others have conducted a variety of activities to 1) determine the geologic, geochemical, and geomechanical properties of the target injection formation and key sealing formations in the vicinity of the injection site; 2) model the effects that large-scale injection of sour CO<sub>2</sub> may have on those properties as well as wellbore integrity; 3) evaluate the geologic risks of this injection process on local and regional scales based on results of the modeling effort; and 4) design a site-specific, risk-based monitoring, verification, and accounting (MVA) approach and technology deployment matrix to ensure safe and effective long-term CO<sub>2</sub> storage.

## 3. Integrated approach to project implementation

The PCOR Partnership applies an integrated approach for implementing large-scale commercial CCS projects that involves feedback loops between the program elements of site characterization, modeling and simulation, risk assessment, and MVA. Knowledge gained in each program element is critical to understanding or developing the other program elements. This philosophy of integration, and its application to the Fort Nelson project in British Columbia, is described in Gorecki and others [1]. Elements of any of those activities are crucial for understanding or developing the other activities. For example, as new knowledge is gained from site characterization, it reduces a given amount of uncertainty in geologic assumptions. This reduced uncertainty can then propagate through modeling, risk assessment, and monitoring efforts. Also, the results of modeling, risk assessment, and monitoring activities (especially baseline monitoring) provide direction for future characterization. Data generated over the course of a project will facilitate the refinement of the operator's understanding of geologic setting and risks. This, in turn, will allow for adjustment of the reservoir model and, if necessary, the MVA plan as a means of further minimizing or mitigating risks. Over time, the operational and MVA data will support the iterative refinement of the reservoir model in such a manner that it becomes a reliable predictor of CCS performance at the project site. This aspect of a project will be critical when issues associated with long-term liability are addressed and oversight of the plume is handed over to the appropriate governing jurisdiction. Fig. 2 provides a graphical representation of the adaptive management approach that was applied to the Fort Nelson project. While the Fort Nelson project is in the "feasibility study" phase, each program element within the integrated approach was addressed.

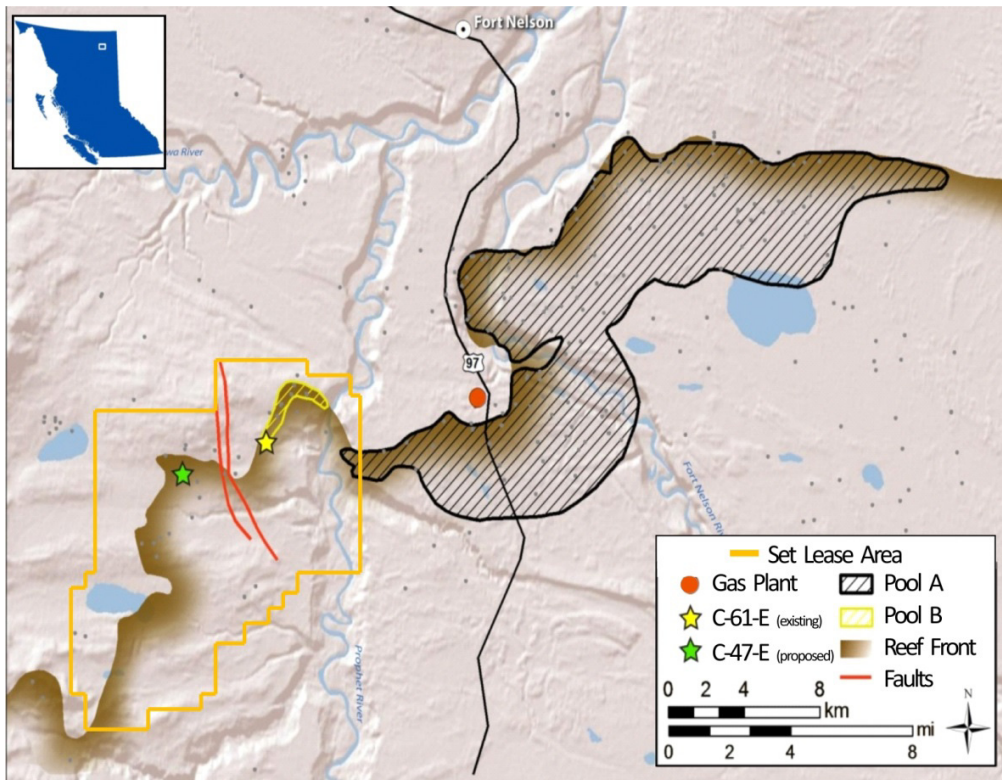


Fig. 1. Map of the Fort Nelson study area, including gas pools, key geologic features, the SET lease area, and well locations. The reef complex extends to the south and east of the reef front line, with a shale basin to the north and west. It should be noted that the reef front shown is for the top of the Devonian-age reef structure, and the middle and bottom portions of the reef complex (where injection would likely occur) actually extend further north and west of the shown front, lying beneath the Fort Simpson shale basin.

#### 4. Fort Nelson site screening, selection, characterization, and modeling

The purpose of the baseline geologic characterization activities for any CCS project is to establish the capacity and integrity of the potential sink–seal systems in the project area. These activities are planned and conducted to address questions related to CO<sub>2</sub> injection operations and determine the key characteristics of those systems as they may apply to long-term storage of CO<sub>2</sub>. These data provide the framework for subsequent predictive modeling, risk assessment, and monitoring design efforts. The geologic characterization of the Fort Nelson area focused on the surface and shallow subsurface environments, deep injection target formations and their associated sealing formations, other formations that may be of interest to project stakeholders (e.g. hydrocarbon-bearing formations, water disposal zones, etc.), and structural features and hydrogeological factors that will control the movement and fate of the injected CO<sub>2</sub>.

As part of the Fort Nelson project, work at the reservoir scale focused on an area within a few kilometers' radius of what is considered to be a potential injection location, with an emphasis on the key underlying and overlying units that may serve as sinks or seals. Local-scale characterization efforts in the Fort Nelson area covered an area tens of kilometers in radius from the injection site. Stratigraphically, the entire sedimentary succession from the basement to the surface was evaluated to some extent at the local scale, although emphasis was placed on the potential sink and seal formations. Work at the regional, or subbasin scale (thousands of square kilometers), evaluated relevant data and information on key geologic formations over the northwestern portion of the Alberta Basin. Hydrogeological systems and the regional continuity of primary sealing formations were the focus of studies at this large scale.

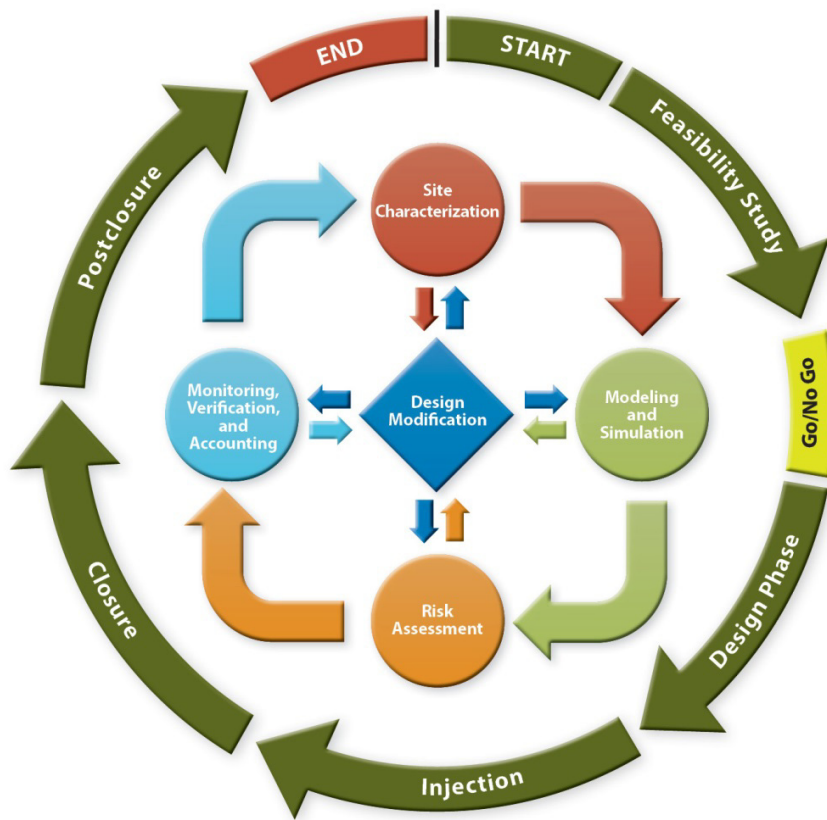


Fig. 2. Graphical representation of the adaptive management approach (modified from Gorecki and others [1]).

Specific geologic characterization efforts for the Fort Nelson project included the following:

- Literature reviews and examination of regional and local surface maps and aerial photos
- Examination, interpretation, and integration of data from 93 wells in the vicinity of FNGP, including well logs, production and injection data, and well testing data
- Drilling, logging, and testing of a deep exploratory test well as well as drilling, logging, and injection testing of a sidetrack of the original deep exploratory test well
- Laboratory-based geochemical, petrophysical, and geomechanical analytical activities using cuttings and core samples from the target injection and sealing formations
- Purchase and interpretation of available historical 2-D and 3-D seismic surveys
- Survey and collection of historical data for existing wells
- Sampling and analysis of shallow groundwater in the vicinity of the exploratory well
- In-depth examination of the hydrogeology of the Mid-Devonian aquifer system

Each of these geologic characterization efforts provided input into the petrophysical reservoir model of the potential Fort Nelson project site. These geologic characterization efforts informed the petrophysical reservoir model by providing information about structure, stratigraphy, formation properties (e.g., porosity, permeability, etc.), faults, and other physical features. The model then served as the platform upon which a series of dynamic injection scheme simulations and history-matching efforts were conducted. The results of the dynamic simulations yielded scheme-dependent predictions of plume geometry, mobility, and fate over the injection and postinjection

periods. Fig. 3 shows a map of potential plume footprint evolution over time based on one of the injection scenarios. The predicted plumes are for an injection scenario (referred to as “Case 5”) that includes three injection wells injecting a total of 2.5 million tonnes/year for 25 years, starting in 2014. The modeling is also a critical tool for determining storage capacity and assessing potential scenarios of leakage to the surface, known natural gas pools, and usable water resources. The insight gained by the modeling activities served as a primary basis for the risk assessment and MVA planning.

## 5. Fort Nelson risk management

The risk management process used by the EERC for managing the subsurface technical risks of the Fort Nelson project is illustrated in Fig. 4 and complies with International Organization for Standardization (ISO) 31000, an international standard for risk management. The risk management methodology described was designed to integrate the ISO 31000 framework with existing SET risk management processes, practices, and risk tolerance standards. To date, the risk assessment for the Fort Nelson project has been implemented in two phases: Round 1 and Round 2. The Round 2 risk assessment, which updated the Round 1 risk assessment, was completed following the collection of additional site and laboratory data and the conduct of additional simulation modeling. In addition to reexamining the subsurface technical risks, the Round 2 risk assessment also included a risk evaluation of an alternative CO<sub>2</sub> injection point. The results of the Fort Nelson risk assessment were used as the basis for developing a draft proposed MVA plan for hypothetical injection schemes.

## 6. Fort Nelson MVA planning

A site-specific, risk-based monitoring plan is designed to mitigate negative impacts and reduce uncertainties by iterative application of monitoring and risk analysis [2]. The trend in recent years among MVA planners has been to integrate site characterization, modeling and simulation, risk assessment, and monitoring strategies into an iterative process to produce robust, broadly defensible MVA plans. It is important to note that the PCOR Partnership and SET activities were conducted to examine the feasibility of a potential CCS project at Fort Nelson. Many steps remain before SET makes a go–no go decision regarding implementation of a CCS project at Fort Nelson. Therefore, the current MVA planning for a potential Fort Nelson project is considered to be hypothetical.

A detailed discussion of the Fort Nelson draft hypothetical MVA plan is beyond the scope of this paper, but the plan includes monitoring elements that cover the surface, near-surface, and deep subsurface environments. Surface water sampling from lakes and streams, shallow groundwater wells, and soil gas-monitoring stations in the vicinity of the deep monitoring and injection wells would allow for monitoring any impacts to the surface and shallow subsurface. The MVA technology matrix for Fort Nelson would include geophysical logs, wellbore integrity monitoring, 3-D seismic surveys, and a variety of downhole instruments (e.g. pressure and temperature sensors) and remote sensing tools. MVA technologies would be deployed at locations selected according to their surface accessibility and spatial relationship to the predicted plume. The timing of MVA events would be planned according to technical need and cost-effectiveness. For instance, operational parameters such as injection rates and reservoir temperature and pressure conditions would be monitored continuously. Surface and shallow subsurface monitoring, such as soil gas and shallow groundwater sampling and analyses, would be conducted seasonally or annually. Deployment of deep reservoir-monitoring tools such as well logs or seismic surveys could be conducted in time steps that range from annually to every 5 years, depending on the technology and the stage of the operation (early-stage deployment would be more frequent than later stage). Fig. 5 illustrates the potential deployment of monitoring technologies at Fort Nelson according to zones (surface, shallow subsurface, and deep subsurface). The locations of potential monitoring activities in relationship to predicted plume geometries for the Case 5 injection scenario are shown in Fig. 3.



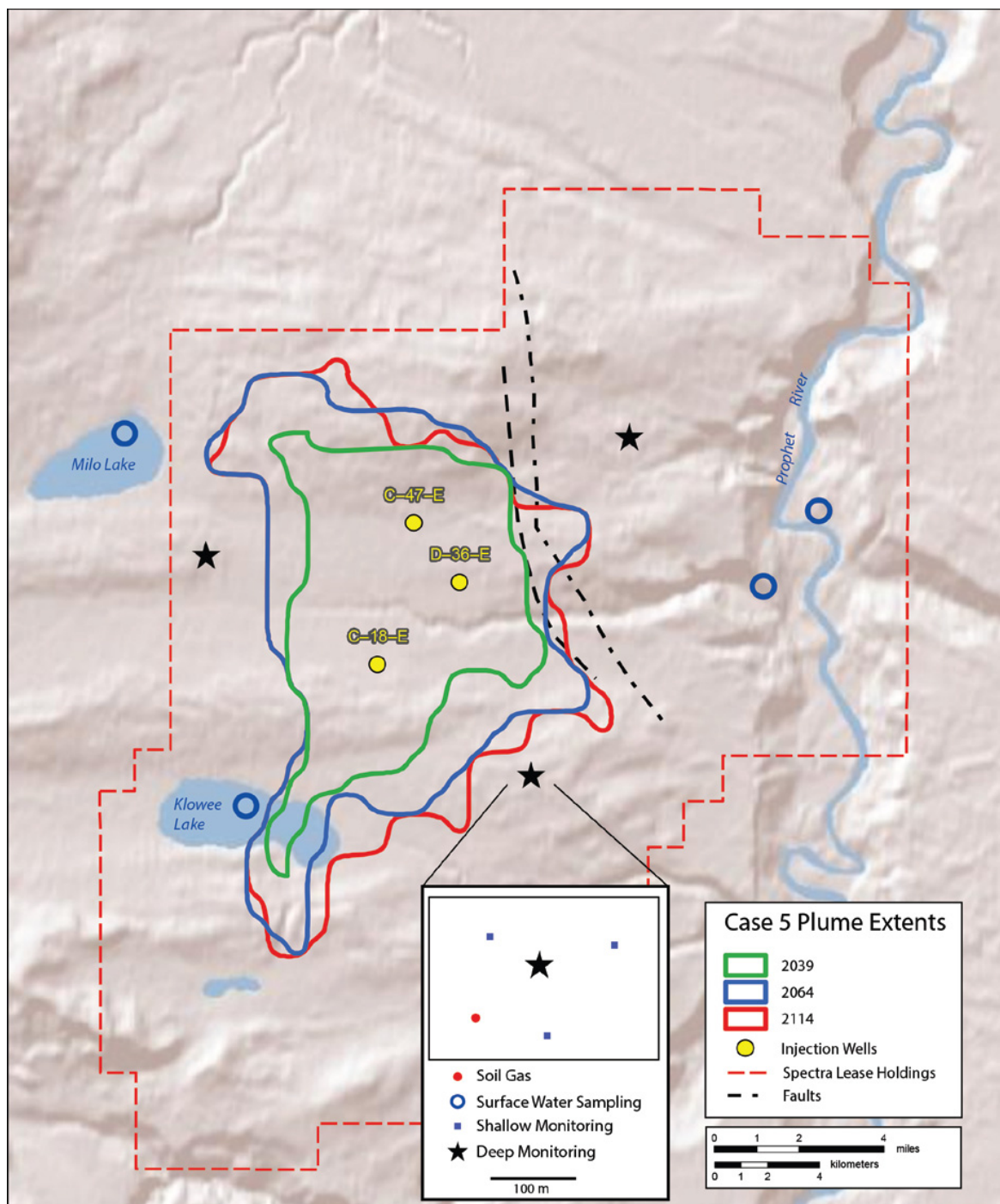


Fig. 3. Map of predicted plume extents over time for one of the potential injection scenarios and locations for monitoring activities.

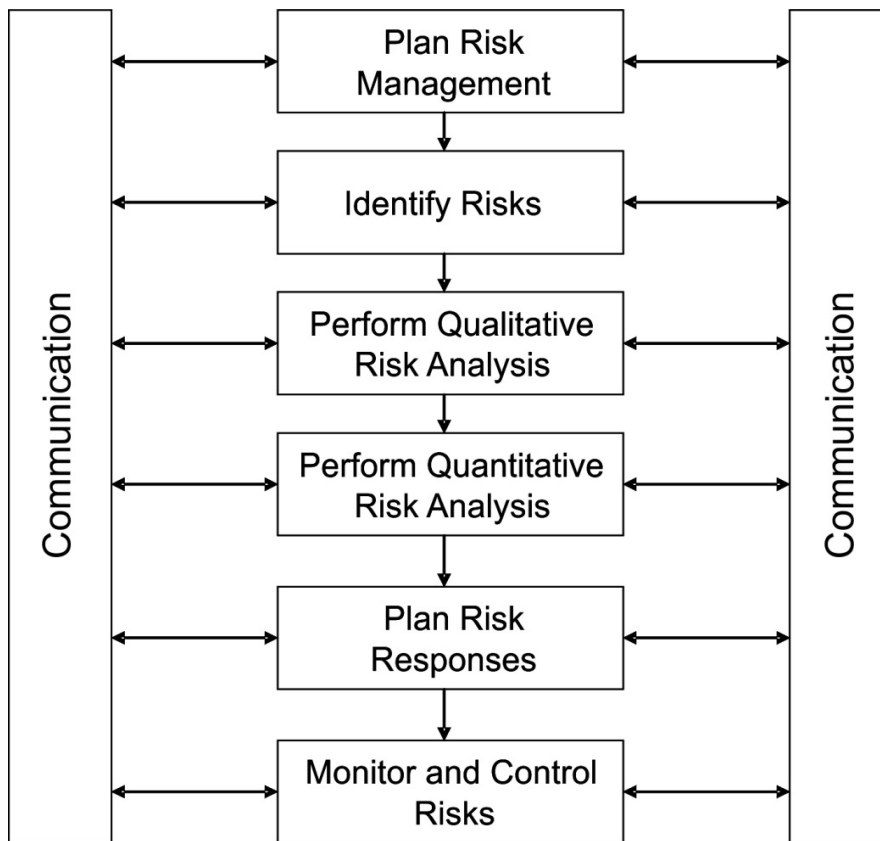


Fig. 4. Risk management framework and process used for the potential Fort Nelson project (modified from International Standard [3]).

One aspect of MVA that is sometimes underappreciated is the effect that geography and climate can have on implementation. At Fort Nelson, those effects are significant. The climate of the Fort Nelson area includes long, cold winters. The landscape is characterized by a poorly drained taiga terrain, much of which is only accessible by ice roads constructed in the winter. This limits the work season for heavy equipment to only a few months each year. In nonwinter seasons, much of the area can only be accessed by small all-terrain vehicles or helicopters. These conditions will limit the number and dictate the location of MVA technology deployment sites. However, while the climate and terrain present challenges with respect to site access and operations, the fact that the oil and gas industry has been able to cost-effectively explore for hydrocarbons and construct and maintain wells and their associated infrastructure for decades under those difficult conditions indicates that MVA at Fort Nelson can also be done. The key to overcoming the challenges presented by climate and terrain at Fort Nelson will be thorough, careful planning and project execution in the field that applies the lessons learned by the local oil and gas industry. The hypothetical MVA plans developed for a Fort Nelson CCS project took into account those challenges and industry experience.

## 7. CSA standard for geologic storage of CO<sub>2</sub> and comparison to Fort Nelson project efforts

In October 2012, the Canadian Standards Association (CSA) released a standard for geologic storage of CO<sub>2</sub> entitled “Z741-12 Geological Storage of Carbon Dioxide.” The standard was developed by CSA’s Technical Committee on Geological Storage of Carbon Dioxide, which is a joint Canada–U.S. Technical Committee. This committee included 38 individuals with a broad range of experience in government, academia, and the oil and gas

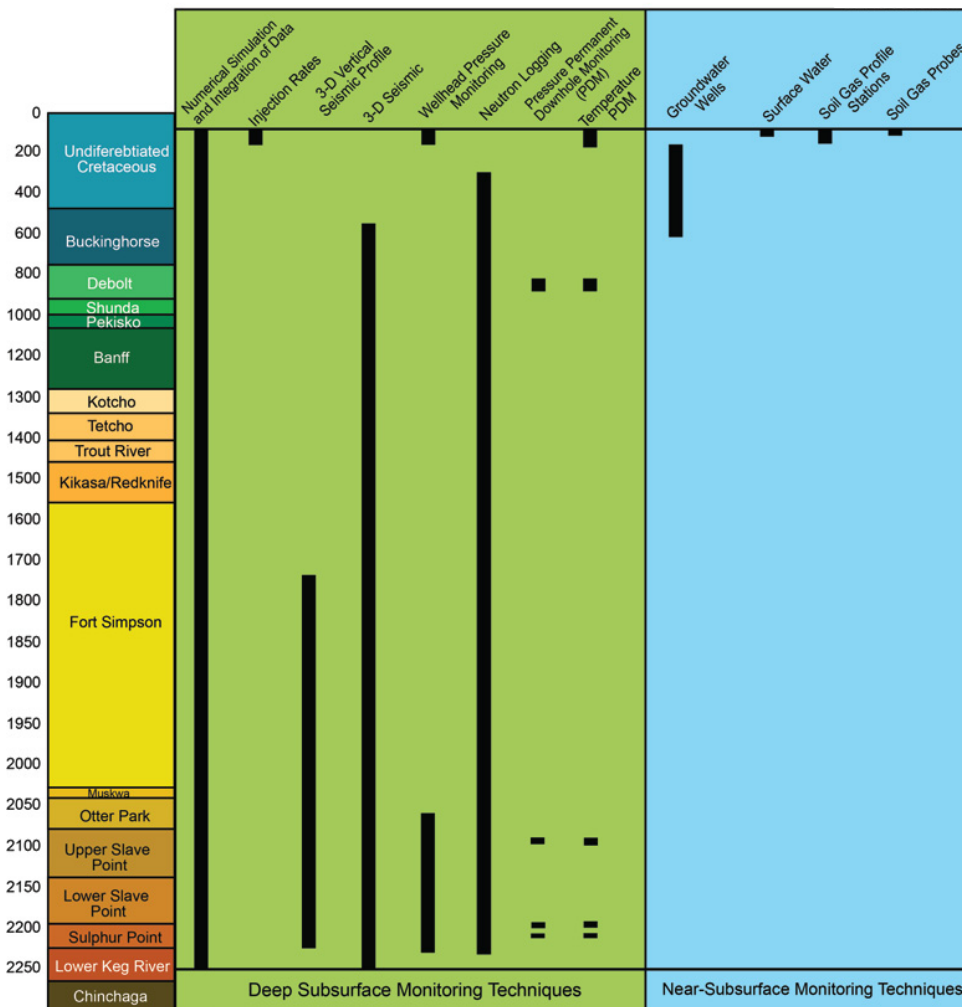


Fig. 5. Hypothetical monitoring technology deployment by zone for a potential Fort Nelson project.

industry. This standard, by itself, does not have the force of law unless it is officially adopted by a regulatory authority [4]. However, it is possible that the CSA standards, in total or in part, could be adopted or referred to by British Columbia regulatory authorities. With this in mind, the Fort Nelson project activities and the draft hypothetical MVA plan were compared to the CSA standard. A brief summary of the CSA draft standard is provided as follows.

The CSA standard can be considered to be comprehensive in that it provides detailed descriptions of practices and procedures for essentially all aspects of a CCS project. Specifically, the CSA standards provide guidance for what it considers to be the six key elements of a CCS project: 1) management systems; 2) site screening, selection, and characterization; 3) risk management; 4) well infrastructure development; 5) monitoring and verification; and 6) cessation of injection. The following is a brief breakdown of the topics covered by the CSA standards within each key project element:

- Management Systems – This section includes standards for the project operator's roles and responsibilities, project stakeholders, continuous improvement, and project definition. Standards for project boundaries



(operational, physical, and organizational), management principles, planning and decision making, resource management, communications, and documentation are also presented.

- **Site Screening, Selection, and Characterization** – This section presents standards for screening, selecting, characterizing, modeling, and assessing a location for geologic storage of CO<sub>2</sub>. Site characterization and assessment are further broken down into standards for the characterization of geologic and hydrogeologic properties of the storage reservoir and confining strata, baseline conditions for geochemical and geomechanical parameters, and existing wells in the vicinity of the proposed project. Standards are also presented for the creation of static geologic models, dynamic flow modeling, geochemical modeling, and geomechanical modeling.
- **Risk Management** – This section provides a very thorough presentation of standards for risk management as applied to a CCS project. Standards are presented for all aspects of risk management including risk planning, assessment, identification, analysis, evaluation, treatment, documentation, communication, and consultation with stakeholders. This section also includes recommendations for the principles and processes associated with each aspect of risk management.
- **Well Infrastructure Development** – This section provides guidance on well construction materials, design, construction schemes, corrosion control, and operation and maintenance. The section on well construction includes guidance on drilling, completions, workovers, abandonment, and restoration.
- **Monitoring and Verification** – This section presents standards for MVA planning, including program design, procedures, and practices. This section also presents a set of MVA specifications that CSA considers to be required and a set of specifications that are considered to be recommended.
- **Cessation of Injection** – This section includes guidance for developing plans for the postinjection and closure periods of a CCS project. This section also includes a description of the qualification process for the postinjection and closure periods.

The CSA standard for geologic storage of CO<sub>2</sub> can be used for different purposes, not only in Canada but internationally as well. One potential scenario is that government agencies may officially incorporate the CSA standard, in whole or in part, into their regulatory processes. There are also other scenarios by which nongovernment stakeholders could use the CSA standard as a benchmark by which CCS projects can be judged both within and outside of the legal system, even in jurisdictions that do not officially adopt the standards. With this in mind, and because the CSA standards are the most detailed and thorough standards of their kind developed by a North American organization, particular attention was paid to comparing the Fort Nelson project efforts to the three aspects of the CSA standard that are most applicable to the efforts to develop an MVA plan: 1) site screening, selection, and characterization; 2) risk management; and 3) monitoring and verification. While management systems, well infrastructure development, and closure are equally important elements of safely and effectively conducting geologic storage of CO<sub>2</sub>, the PCOR Partnership efforts at Fort Nelson did not cover those aspects so they were not included in the comparison.

The CSA standard presents criteria for site screening, site selection, site characterization and assessment, and modeling for characterization. There are 13 criteria that address the technical, legal, and regulatory aspects of site screening. Site selection is addressed by 29 surface and subsurface criteria. Over 60 criteria aimed at site characterization and assessment are presented for geologic, hydrogeologic, geochemical, geomechanical, and well characterization. Modeling for characterization is covered by approximately 100 criteria that are devoted to static modeling, flow modeling, geochemical modeling, and geomechanical modeling. A comparison of the CSA standards to efforts conducted by SET and the PCOR Partnership shows that those efforts clearly address all of the site selection, characterization, and modeling criteria. In fact, in a majority of the categories, the Fort Nelson efforts to date exceed many of those CSA standards. A generalized summary of that comparison is shown in Fig. 6.

With respect to risk assessment, the CSA standard includes approximately 120 specifications for risk management. Areas of risk management that the CSA standard addresses include objectives, context, risk management planning, risk assessment, planning and review of risk treatment, review and documentation, and risk communication and consultation [4]. The Fort Nelson risk assessment efforts address all of those criteria and, in many cases, go beyond the CSA specifications. Fig. 7 presents a generalized summary of that comparison.

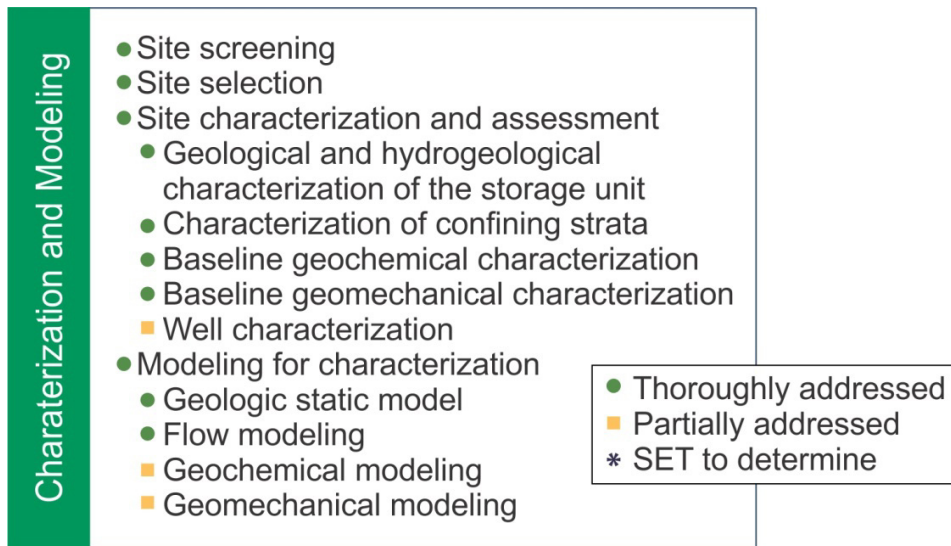


Fig. 6. Generalized summary of Fort Nelson characterization and modeling compared to CSA standards.

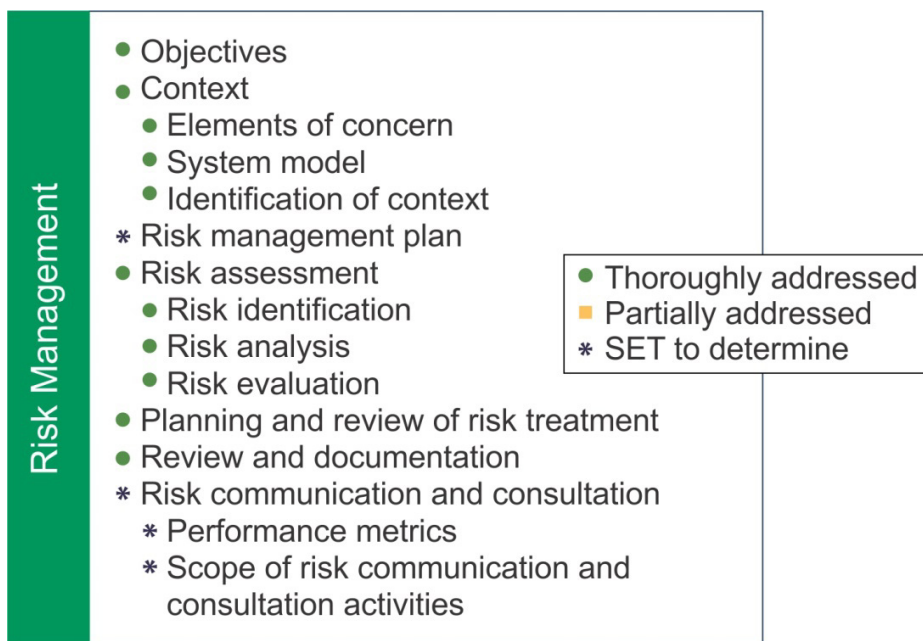


Fig. 7. Generalized summary of Fort Nelson risk management compared to CSA standards.

Regarding MVA, the CSA standard presents many monitoring and verification program-required specifications. These specifications range from the relatively straightforward and mundane, such as planned injection rates and total mass of CO<sub>2</sub> to be stored, to complex subjects that require multidisciplinary study. An example of the latter is a specification which states that the MVA plan is required to include “the risk-based ranking of scenarios that have the potential to cause significant health, safety, or environmental impact or to negatively affect storage performance.... This description should encompass the link between monitoring and verification design and any updated risk assessment results in compliance with the risk assessment criteria....”

Generally speaking, while the CSA standard enumerates in significant detail the expectations for the types of information that are required and recommended in an effective MVA plan, the standard does not prescribe the use of specific technologies in either the acquisition of baseline data or the monitoring of injected CO<sub>2</sub>. CSA states that “the purpose of monitoring and verification is to address health, safety, and environmental risks and assess storage performance. Monitoring, verification, and accounting activities support a risk management strategy that enables an assessment of storage performance and provides confidence that greenhouse gas reductions are real and permanent.” This passage is relevant because it is an example of CSA’s tendency to directly link risk assessment and management with the development of an effective MVA plan. The linkage of MVA to risk analysis is a theme that runs strongly throughout the CSA standard document.

CSA states that the MVA program must provide information on 19 different categories. Some of the categories are further broken down into subcategories, with each requiring its own specific information. This results in a total of approximately 80 criteria that must be addressed by the MVA planning activities. Major categories for which standards are enumerated include MVA purpose, program periods (i.e., preinjection, injection, closure, and postclosure periods), program objectives, and program design. The CSA standards offer brief, generalized guidelines with respect to MVA purpose and program periods. MVA program objectives are addressed by 12 criteria, while over 60 criteria are presented for MVA program design. The program design section includes 28 required specifications and 23 recommended specifications. A detailed description of how each of the elements of the hypothetical Fort Nelson MVA plan compare to all of these criteria and specifications is beyond the scope of this paper. However, a comparison of the CSA standards for monitoring and verification to the MVA approach and technology matrix being considered for a hypothetical Fort Nelson project indicates all of the required specifications and a majority of the recommended specifications would be adequately addressed. The challenges associated with limited site accessibility because of climate and terrain may preclude Fort Nelson CCS operations from fully implementing many of the recommended MVA protocols and technologies, but should not prevent the application of those that are required under CSA standards. A generalized summary of that comparison is provided in Fig. 8.

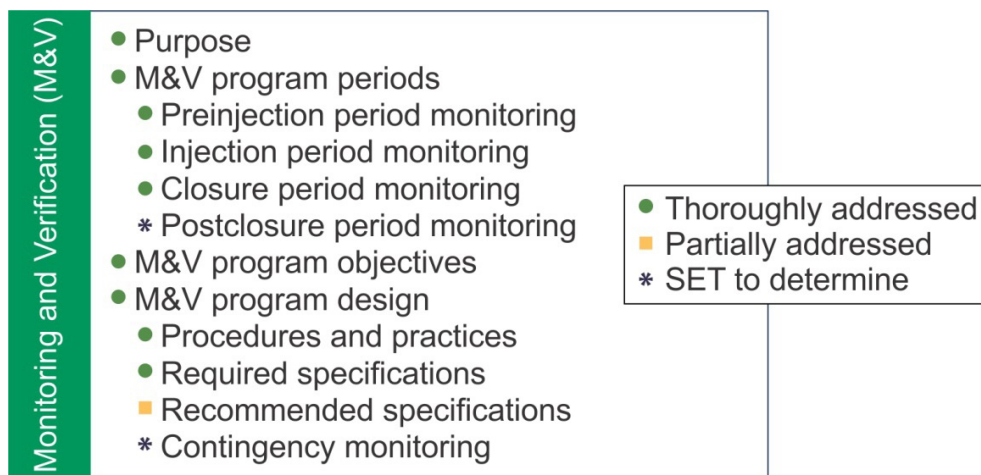


Fig. 8. Generalized summary of Fort Nelson MVA planning compared to CSA standards.

## 8. Conclusions

The results of characterization, modeling, and risk assessment efforts conducted as part of the Fort Nelson CCS feasibility study suggest that a commercial-scale CCS project in the Fort Nelson area may be technically feasible. Climate and terrain will hamper the deployment of some MVA technologies, but implementation of an effective MVA plan for both surface and subsurface environments can be achieved by the application of proven approaches used by the oil and gas industry in the area. Acknowledging the need for longer lead times for planning and elevated levels of coordination between different technical teams and service providers will be keys to successful MVA deployment and operation at Fort Nelson. With respect to compliance with the CSA standards for geologic storage of CO<sub>2</sub>, if it were to go forward, the Fort Nelson CCS project would need to elaborate on a number of items in order to be fully compliant with the standards. Specifically, additional efforts would be needed in the areas of geochemical and geomechanical modeling, characterization of neighboring wellbores with respect to wellbore integrity, risk management communication planning, postclosure and contingency MVA planning, enumeration of specific performance metrics, and detailed schedules for specific MVA activities and reporting. Most of these topic areas are beyond the scope of a feasibility study but, in the event that SET was to decide to move the project forward, they would be included in the design phase of a CCS project.

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